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August 6, 1968

A MANUALLY THROTTLED THRUST PROFILE FOR DOI

By Otis F. Graf,

Guidance and Performance Branch

MISSION PLANNING AND ANALYSIS DIVISION

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HOUSTON, TEXAS

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PROJECT APOLLO

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1.0 SUMMARY

When the DOI maneuver is performed under automatic LGC control, the LGC commands the DPS engine to burn at a 1050-lb thrust for approximately 70 seconds. The SHe tank pressure rises rapidly (as a function of DPS burn time) under these conditions, to a point which is close to or in excess of the tank design limit. Consequently, it is desirable to perform the DOI burn in as short a time interval as possible.

A method by which the SHe tank pressure build-up could be reduced is to manually throttle the DPS engine to the intermediate thrust level of 40 percent of maximum thrust after a 15-seconds engine trim time at 10 percent. The increased thrust acceleration at 40 percent would shorten the DPS burn time and therefore reduce the rise in the SHe tank pressure. Also, this would allow a crew checkout of the manual throttle since manual throttle capability is needed for the final period of powered descent.

2.0 INTRODUCTION

The descent orbit is a Hohmann type transfer from the 60-n. mi. circular lunar orbit down to the point of initiation of powered descent. The descent orbit has an apocynthion of 60-n. mi. and a pericynthion of 50 000 ft. The maneuver takes place behind the moon, 180° from the landing site, and is targeted from the ground. The guidance to be used most probably will be external ΔV. This is a critical burn, and accuracy is very important because of the chance of lunar impact. The required V_g is in the range of 70-72 fps from the nominal (60-n. mi. by 60-n. mi.) orbit and is in the negative X direction (local vertical system).

The DPS thrust profile for DOI has undergone some consideration and change in recent months. The LGC is currently programmed to perform DOI in 70 sec at 1050 lb of thrust. However, there are some engine constraints and mission objectives that suggest a DPS duty cycle which includes a manual throttle-up to 4200 lb (40 percent of full thrust). The intention of this document is to explain the reasons behind this proposed thrust profile and to show that it is feasible and more desirable than the automatic LGC controlled DPS thrust profile for DOI.

3.0 SYMBOLS

ARMP	Apollo Reference Mission Program
c.g.	center of gravity
DOI	descent orbit insertion
DPS	descent propulsion system
FTP	fixed throttle position
LGC	lunar module guidance computer
LLM	lunar landing mission
LMS	lunar module simulator
PGNCS	primary guidance, navigation, and control system
SHe	super-critical helium
t_{go}	time-to-go to DPS engine cutoff
TTCA	thrust and translation control assembly
V_g	required velocity-to-be-gained magnitude for DOI
ΔV	sensed velocity change during the maneuver time

4.0 THE ADVANTAGES OF THE NEW THRUST PROFILE

The automatic LGC profile is shown in figure 1(a) and the new thrust profile for DOI is shown in figure 1(b). The new profile was chosen over the old because it has two distinct advantages. They are:

(1) A lower peak in the super-critical helium (SHe) tank pressure.

(2) A checkout of the DPS manual throttle before its required use during the final period of the descent burn.

The SHe tank pressure is critical on the lunar landing mission. More definition of this problem is given in the following section. The checkout of the manual throttle is a crew request. However, it was under consideration to put into the LGC the capability to automatically throttle the DPS to an intermediate thrust level. The automatic capability was not included when it was found that this function could satisfactorily be done manually.

5.0 THE SHe TANK PRESSURE PROBLEM

The pressure of the DPS SHe tanks is of concern during the lunar mission until the DPS duty cycle has ended. The SHe pressure rises during the mission and reaches a peak during the powered descent burn. This peak can vary, depending on the following:

(1) The thrust profile of the previous DPS burn (DOI)

(2) The pressure after loading on the pad

(3) The length of time since loading

(4) The pressure rise rate after loading

An empirical simulation of the SHe system was used to evaluate different DPS duty cycles for the lunar mission. The program used in the simulation is described in reference 1. Figures 2, 3, 4, and 5 contain plots of SHe pressure vs time for different DPS duty cycles. The descent burn profile is the same in each case and was taken from reference 2. The peak in pressure during the powered descent burn is our main concern; it is desirable that it does not exceed the design limit (1710 psia).

Also plotted on figures 2, 3, 4, and 5 is the DPS duty cycle vs time from DOI ignition. The DOI V_g considered here is nominal (70 fps). The difference between each of these figures is the thrust profile for DOI. They are as follows:

(1) Figure 2 - 10 percent thrust for 70 seconds.

(2) Figure 3 - Manual throttle-up to 30 percent after 15-sec trim time.

(3) Figure 4 - Manual throttle-up to 40 percent after 15 sec trim time.

(4) Figure 5 - Manual throttle-up to 52.7 percent (soft stop) after 15 sec trim time.

Each of the figures 2, 3, 4, and 5 is a set of four. For each figure there are the following four cases:

(a) Time from opening of earth launch window to DOI = 104 hr; pressure rise rate during coast = 8.5 psia/hr.

(b) Time from opening of earth launch window to DOI = 104 hr; pressure rise rate during coast = 10 psia/hr.

(c) Time from opening of earth launch window to DOI = 120 hr; pressure rise rate during coast = 8.5 psia/hr.

(d) Time from opening of earth launch window to DOI = 120 hr; pressure rise rate during coast = 10 psia/hr.

In (a) and (b) above, the time from opening of earth launch window to DOI is the maximum time expected (ref. 3) without an allowance for lighting adjustment. In (c) and (d), 16 hr in lunar orbit was added for lighting adjustments. The rise rate of 8.5 psia/hr is the actual LM-3 rate (ref. 4). The rise rate of 10 psia/hr is the LM data book value (ref. 5). Other assumptions made in this simulation include:

(1) The pressure after pad loading is 120 psia.

(2) The time from pad loading to first launch window opening is 27 hr.

(3) After the DPS burn at DOI there is a pressure rise of 50 psia due to heat soak back.

Figures 2, 3, 4, and 5 show the problem encountered with the SHe pressure. The SHe system contains burst disks which will relieve the pressure when it gets within the range of 1870-1968 psia, but then the entire helium supply is lost and the mission must be aborted. The cases with manual throttle-up to an intermediate thrust level do not solve the problem in every case, but they do give a desirable lowering of the peak pressure.

6.0 MANUAL THROTTLING OF THE DPS

6.1 Operation of the Automatic DPS Throttle-Up

A discussion of DPS operation while under automatic throttle control will show why it is necessary for a manual throttle control of the DOI maneuver. When under PGNCS control, the DPS is held at 10 percent thrust until a preselected time (LGC erasable quantity) after ignition and then is throttled up to FTP. The PGNCS does not have the capability to automatically throttle to an intermediate level. This initial time at 10 percent is called the "trim time" since during this time the engine thrust vector is being trimmed through the c.g. The objective is to obtain complete vehicle stability and control with the DPS before the engine is throttled up. A long trim period is required because of a slow engine gimbal drive rate (.2°/sec); uncertainty in the trim of the thrust vector; and uncertainty in the c.g. location, which is due primarily to the movement of fuel through the tank interconnect. This interconnect allows the movement of propellant between the two propellant tanks and likewise for the oxidizer.

It was found that some maneuvers required a shorter trim time (a function of fuel loading) than others and this time has been assigned an erasable location in the LGC. There is a redundant check in the LGC which will inhibit the throttle-up when the DOI maneuver is performed, regardless of how long the trim time is. This check requires that in order to get throttle-up, the V_g must be large enough so that the maneuver time at 10 percent thrust will be greater than 95 seconds. With the vehicle weight (33 200 lb) and V_g (70-72 fps) for DOI, this test is not satisfied and throttle-up will always be inhibited. The original purpose of this check will be explained later in this document. It has so far been shown that in order to perform the DOI maneuver at any DPS thrust other than 10 percent, the DPS must be throttled manually.

6.2 Required Minimum Trim-Time

The required trim time for DOI is a function of the mistrim of the thrust vector through the c.g. The trim time must not be so short that it leads to a control problem, excessive RCS fuel usage, or violation of engine constraints. Also, it must not be so long that it will jeopardize an accurate cut-off (see section 6.3) or prohibit a desired short burn time.

The trim time chosen for DOI is 15 seconds. This time satisfies the criteria stated above. According to reference 6, the root-sum square of all the 3-σ errors gives a mistrim of $\pm$ 1.8° at DOI ignition. Also according to reference 6, a trim time of 15 seconds and throttle-up to 40 percent will not result in the use of any additional RCS fuel.

6.3 Requirements for An Accurate Cut-Off

In order to get an accurate cut-off, the general requirement is that the thrust must be constant during the last six seconds before engine cut-off. This is due to the computation cycle of two seconds in the LGC and because the acceleration is computed by measuring the change in velocity every two seconds. Thus, if there is a significant change in thrust between these measurements, the computed acceleration over that two second interval will not be the true acceleration. The computed acceleration is used in the time-to-go to cutoff (t_{go}) equations. In addition, once t_{go} is 4 seconds or less, a clock is set and the engine is cutoff at $t = t_{present} + t_{go}$. The result is that after throttle-up there is a minimum amount of burn time needed after thrust stabilization in order to have an accurate cutoff, and this minimum time depends upon at what point in the two second computer cycle the thrust stabilization occurs.

To determine this minimum time, a test was made as follows: First, it was assumed that throttle-up and thrust stabilization could occur at any time in the computer cycle. Then the Apollo Reference Mission Program (ARMP) simulation was run using the DPS thrust profile in figure 6. The point of thrust stabilization at FTP (9869.61-lb thrust) occurred 27 seconds after ignition (includes 26 seconds of trim time at 10 percent and a 1-second build-up to FTP).

Cases were run in which the thrust stabilized at different points in the computer cycle, and these were compared with the case in which thrust stabilization and an LGC computer cycle conincided (considered the nominal case). Comparison cases were obtained by using different targets which would result in a thrust termination 4, 5, 5.5, and 6 seconds after thrust stabilization. The results of this study are given in table I and the explanation of this table is as follows: The "nominal x-second burn at FTP" is a burn whose external ΔV targets are such that (using the profile in figure 6) an LGC commanded cutoff occurred x-seconds after thrust stabilization and a computation cycle. In this case thrust stabilization and the computation cycle coincide. These targets are listed as "nominal ΔV = y fps". Then these same targets were rerun such that thrust stabilization occurred .1, .3, .5, ..., 1.9 seconds after a computer cycle. The actual cutoff time in seconds after FTP stabilization and the actual accumulated ΔV's are listed. These results show that when it is assumed that thrust stabilization can occur at any point in the computer cycle, only a burn profile which includes at least 6 seconds of thrust after stabilization will always result in an accurate cutoff.

An explanation can be given for the test which can prevent throttle-up, as described in section 6.1. Figure 7 shows accumulated ΔV vs vehicle weight. There are two curves, one for each of the following two DPS thrust profiles:

(1) 95 seconds at 1050 lb thrust.

(2) 26 seconds at 1050 lb thrust plus 6 seconds at FTP.

It is considered that a worst case mistrim would require a 26-second trim time. This coupled with a 6-second minimum time at FTP defines the thrust profile described in (2) above. Throttle-up to FTP will not occur unless the maneuver requires at least 95 seconds at 10 percent. But from figure 7 it is seen that the ΔV resulting from thrust profile (1) is always greater than that due to thrust profile (2). Therefore, when the trim time is 26-seconds, throttle-up will not occur unless an accurate cut-off is assured.

6.4 Pilot Reaction Time

In order to determine the feasibility of manual throttling for DOI, tests were run on the LMS. The primary purpose of these tests was to determine the pilot's reaction time in moving the throttle. Once his reaction time is known, we can then determine his ability to follow the nominal thrust profile and stabilize the thrust in time to give an accurate cutoff.

Four astronauts participated in the tests. The engine ignition and throttle-up to 10 percent were done automatically. The objective of this test was to throttle the engine to 40 percent, 10 seconds after the 10 percent level was reached. The pilot started a clock when he saw the percent engine thrust indicator reach 10 percent. When the clock read 10 seconds, he moved the throttle up from 10 percent to 40 percent. Two reaction times were observed:

(1) his delay in initiating the throttle-up,

(2) his delay in moving the throttle to the 40 percent thrust level.

These delay times are listed in table 2. The average for the first delay time is 1.01 seconds and for the second delay time is 2.11 seconds. In each case, the pilot came within ± 2 percent of the 40 percent level. Thus, we observe a total average delay of 3.12 seconds. It should be noted that none of these pilots had previous experience in performing this maneuver. Therefore, in this document the average time (3.12 seconds) will be considered the worst case for manual DPS throttling.

7.0 SELECTION OF AN INTERMEDIATE THRUST LEVEL FOR DOI

It now remains to show how the intermediate thrust level in the new DPS thrust profile for DOI was selected. The three thrust levels which were considered were: 30, 40, and 52.7 percent. The 52.7 percent level was considered since it is the value at the soft stop of the TTCA. The three thrust levels cover most of the throttleable region.

From figures 3, 4, and 5 it can be seen that there is only a little difference between the three in the SHe pressure peaks that they produce. We will select the highest throttle of the three that will give an accurate guided cutoff for any DOI V_g magnitude that can be expected. In this respect the worst case would be a DOI maneuver from a 50-n. mi. lunar orbit. The V_g magnitude from this orbit is approximately 58 fps.

The DOI maneuver was simulated in the ARMP and external ΔV guidance was used. The three thrust profiles that were used are shown in figure 8. All of these profiles include the worst case astronaut delay times described in section 6.4. Considered first was the V_g of 70 fps; i.e. from the nominal 60-n. mi. circular lunar orbit. The following results were obtained:

Intermediate Thrust Level, percent	Total DPS Burn Time, sec	Time From Thrust Stabilization At The Intermediate Thrust Level to Cutoff, sec
30	34.34	16.24
40	30.01	11.91
52.7	26.89	8.77

The three times in the right hand column above correspond to the "x" in figure 8. All three of the above cases satisfy the criteria for accurate cutoff described in section 6.3.

Next a DOI ΔV of 58 fps was considered. This is the case that would most seriously endanger an accurate cutoff since it is the minimum ΔV expected for DOI. The results are as follows:

Intermediate Thrust Level, percent	Total DPS Burn Time, sec	Time From Thrust Stabilization At The Intermediate Thrust Level to Cutoff, sec
30	30.40	12.28
40	27.06	8.94
52.7	24.65	6.53

Again, the three times in the right hand column above correspond to the "x" in figure 8. Throttle-up to soft stop gives only marginal conditions for an accurate cutoff. Throttle-up to 40 percent still gives 3 seconds to spare. Therefore, 40 percent was chosen as the proper intermediate thrust level for DOI. Our simulation included worst case dispersions in lunar orbit altitude and astronaut throttling delays and the 40 percent thrust level still gave an accurate cutoff. The nominal DPS profile for DOI from a 60-n. mi. lunar orbit is shown in figure 1(b).

8.0 CONCLUDING REMARKS

If the DOI maneuver is completely controlled by the PGNCS, the resulting burn will be at 10 percent thrust for approximately 70 seconds. It has been shown that this thrust profile will increase the SHe tank pressure to a point close to or exceeding the tank design limit. To minimize the SHe tank pressure problem, the DOI maneuver should be performed in as short a time interval as possible. This can be accomplished by manually throttling to 40 percent after a trim time of 15 seconds. When this new thrust profile is incorporated into the complete DPS duty cycle for the LLM, the following advantages are realized:

(1) A lower peak in the SHe tank pressure

(2) Operation of the DPS at a more efficient thrust

(3) Checkout of the DPS manual throttle before the descent burn

This manual throttling procedure for DOI is completely compatible with the thrust translation control assembly (TTCA), the descent propulsion system, external ΔV guidance, and accuracy requirements.

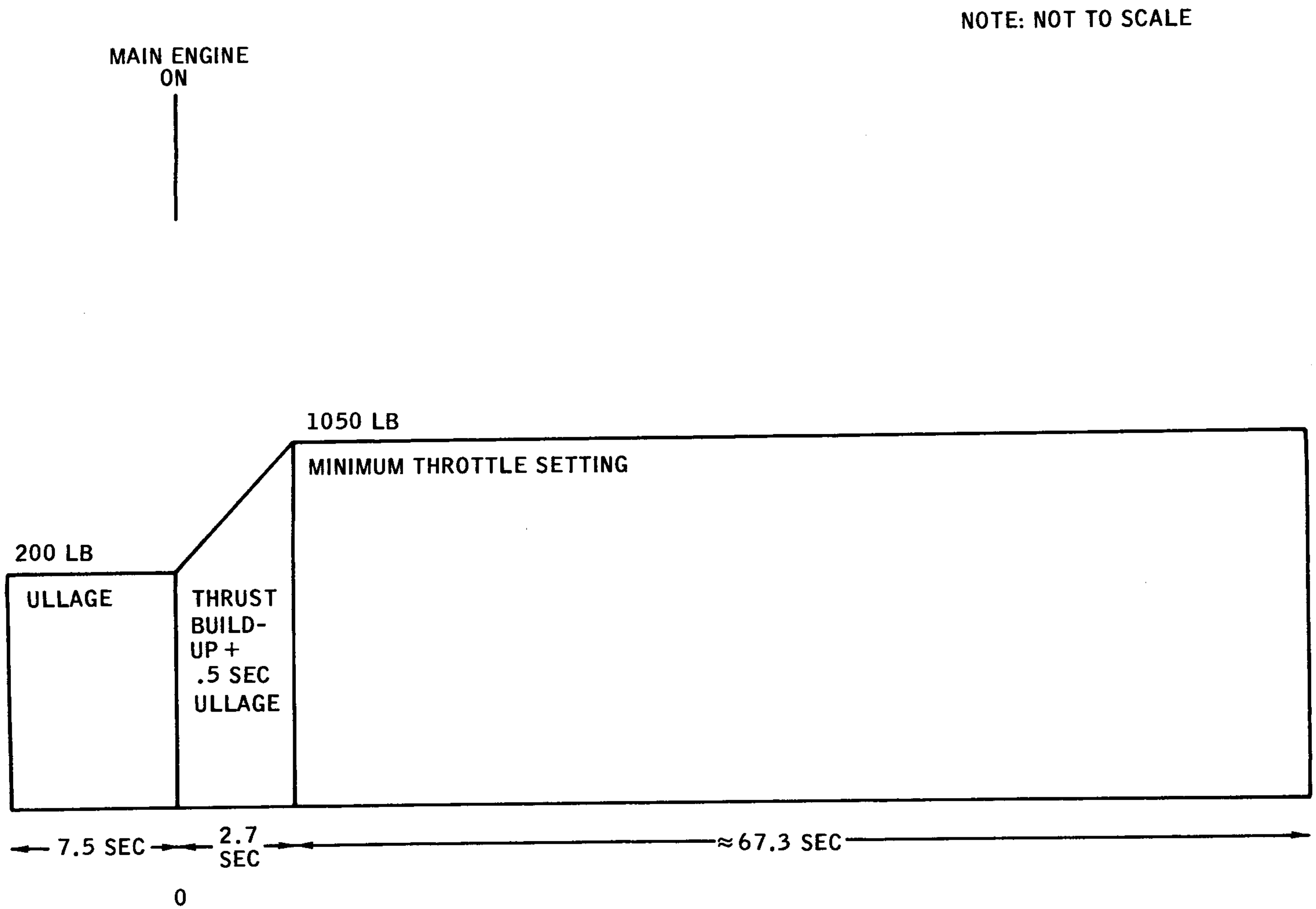
TABLE I.- CUTOFF ACCURACY DATA

	Δ Time after last computation cycle when throttle-up occurs, sec									
	.1	.3	.5	.7	.9	1.1	1.3	1.5	1.7	1.9
	Nominal 4-sec burn at FTP; Nominal ΔV = 80.9794 fps									
Actual time at FTP, sec	4.049	4.164	4.309	4.491	4.714	4.001	4.001	4.001	4.001	4.001
Actual ΔV at cutoff, fps	81.4823	82.6690	84.1753	86.0518	88.3582	80.9874	80.9892	80.9911	80.9928	80.9956
	Nominal 5-sec burn at FTP; Nominal ΔV = 91.3172 fps									
Actual time at FTP, sec	5.072	5.235	5.433	5.001	5.002	5.002	5.002	5.002	5.002	5.002
Actual ΔV at cutoff, fps	92.061	93.744	95.796	91.331	91.332	91.335	91.336	91.338	91.339	92.342
	Nominal 5.5-sec burn at FTP; Nominal ΔV = 96.4905 fps									
Actual time at FTP, sec	5.584	5.501	5.502	5.502	5.502	5.502	5.502	5.503	5.503	5.503
Actual ΔV at cutoff, fps	97.3548	96.5053	96.5070	96.5092	96.5105	96.5126	96.5143	96.5160	96.5177	96.5200
	Nominal 6-sec burn at FTP; Nominal ΔV = 101.662 fps									
Actual time at FTP, sec	6.002	6.002	6.002	6.002	6.002	6.003	6.003	6.003	6.003	6.003
Actual ΔV at cutoff, fps	101.683	101.685	101.687	101.689	101.690	101.692	101.694	101.696	101.697	101.700

TABLE 2.- ASTRONAUT DELAY TIMES

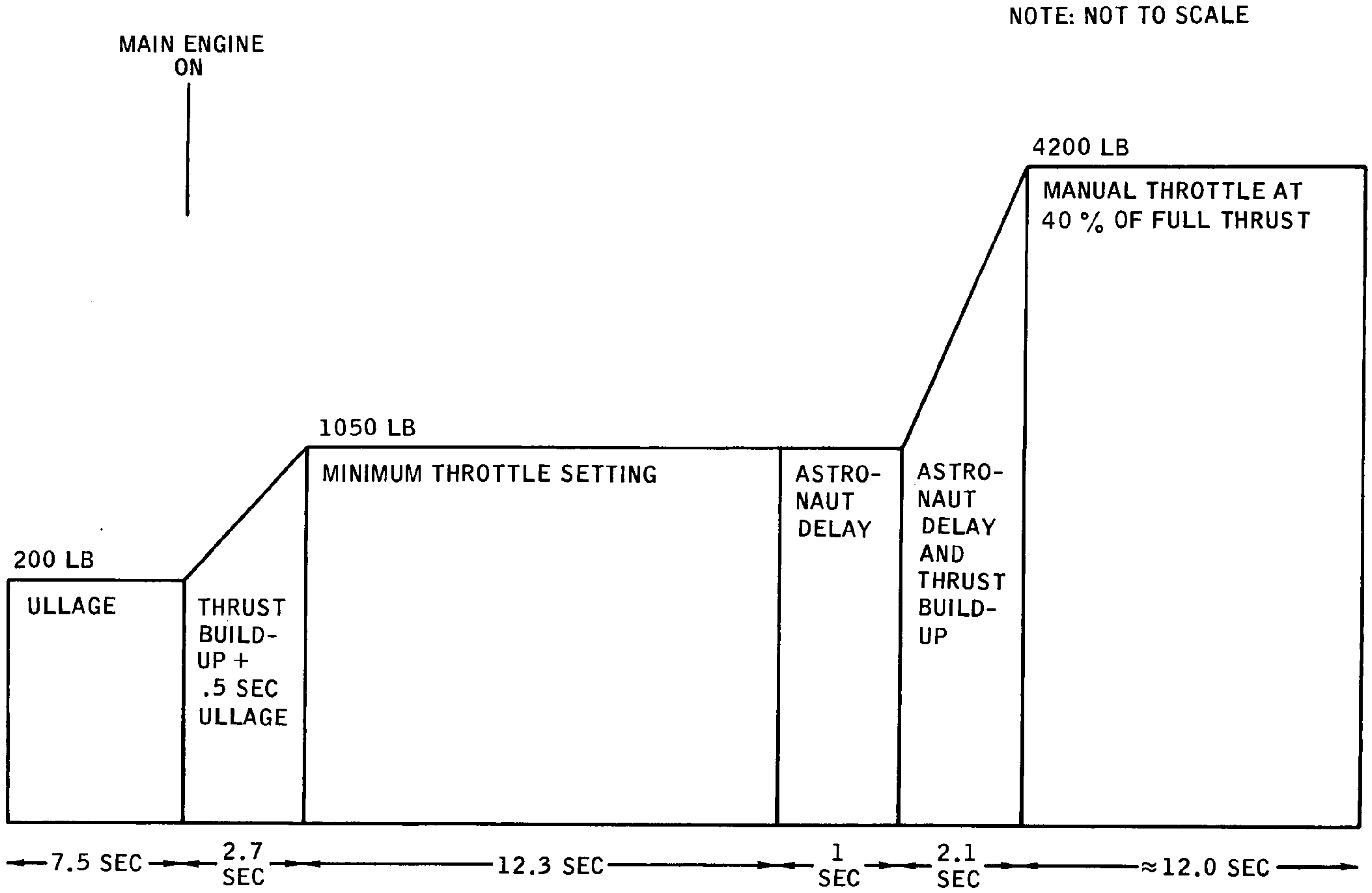
Pilot	Astronaut delay in initiating throttle-up, sec	Manually throttled thrust build-up time from 10% to 40%, sec
A(1)	1.27	2.4
A(2)	1.67	1.74
A(3)	2.61	1.5
B(1)	.27	2.11
B(2)	.20	2.28
B(3)	.29	1.66
C	.78	1.87
D	.99	3.32
Average of all manual runs	1.01	2.11

Note: Four pilot subjects participated in the tests. Two made three runs each and two made one run each.



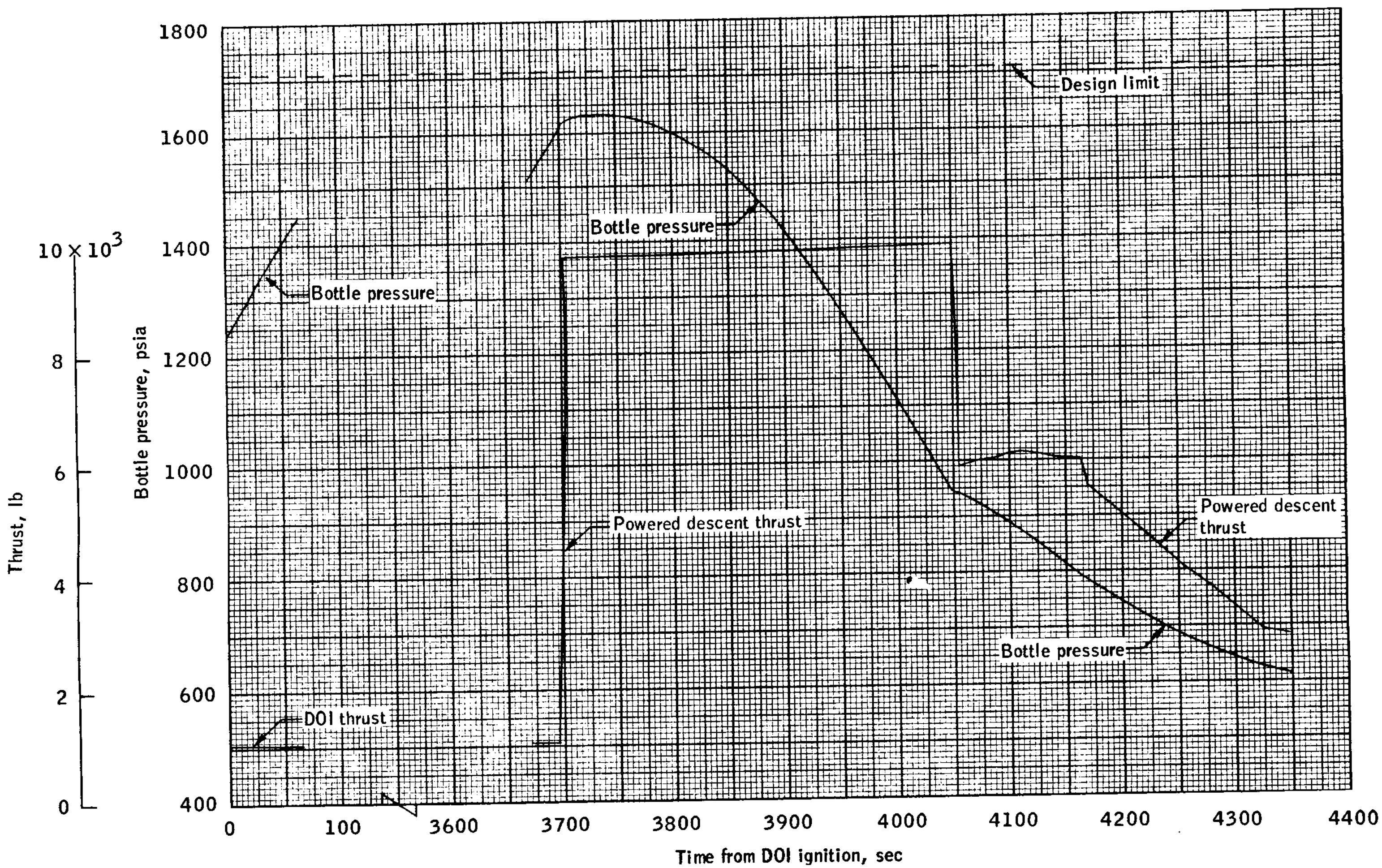
(a) No throttle-up.

Figure 1.- Nominal DPS thrust profile for DOI.



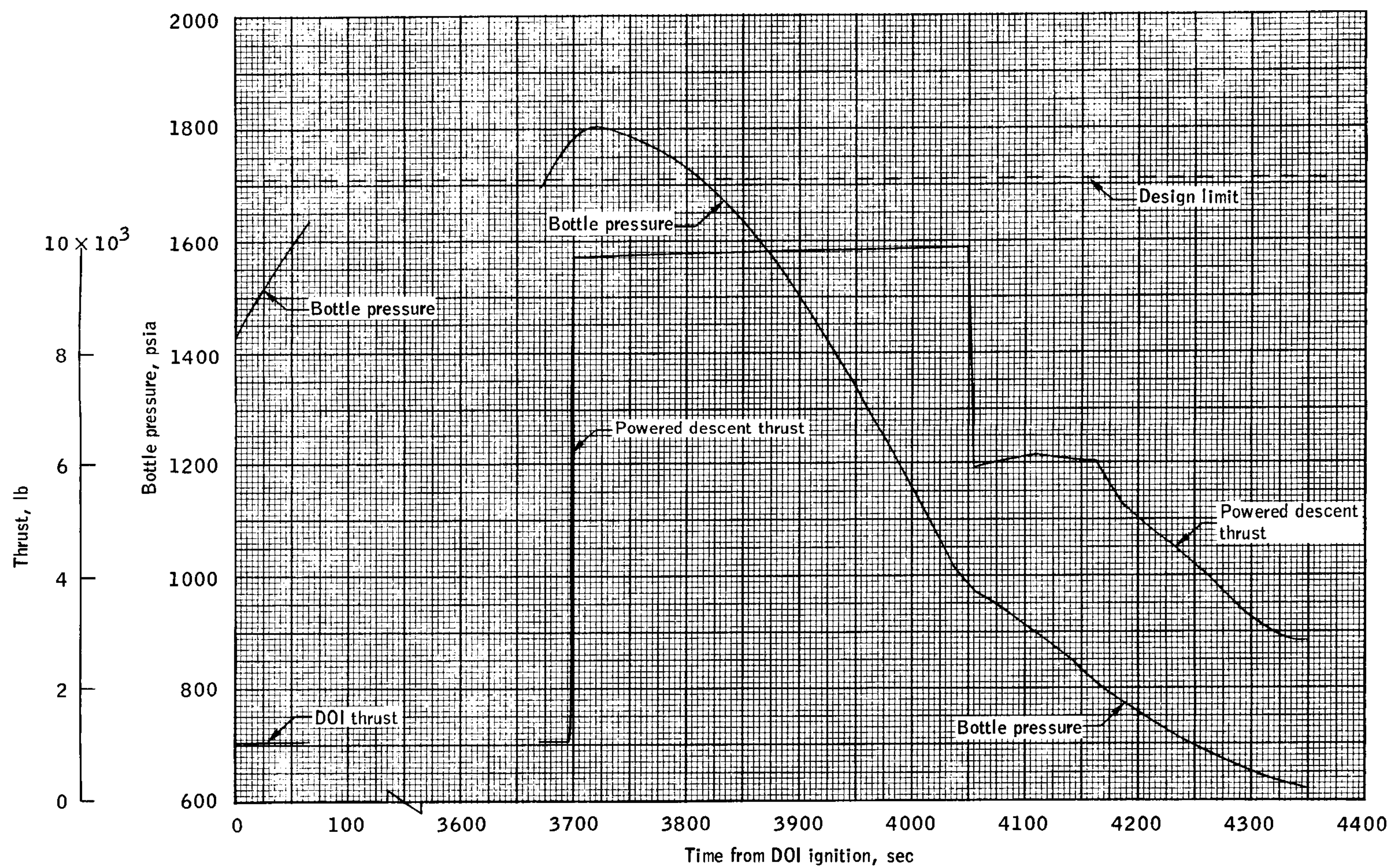
(b) Manual throttle-up to 40 %.

Figure 1.- Concluded.



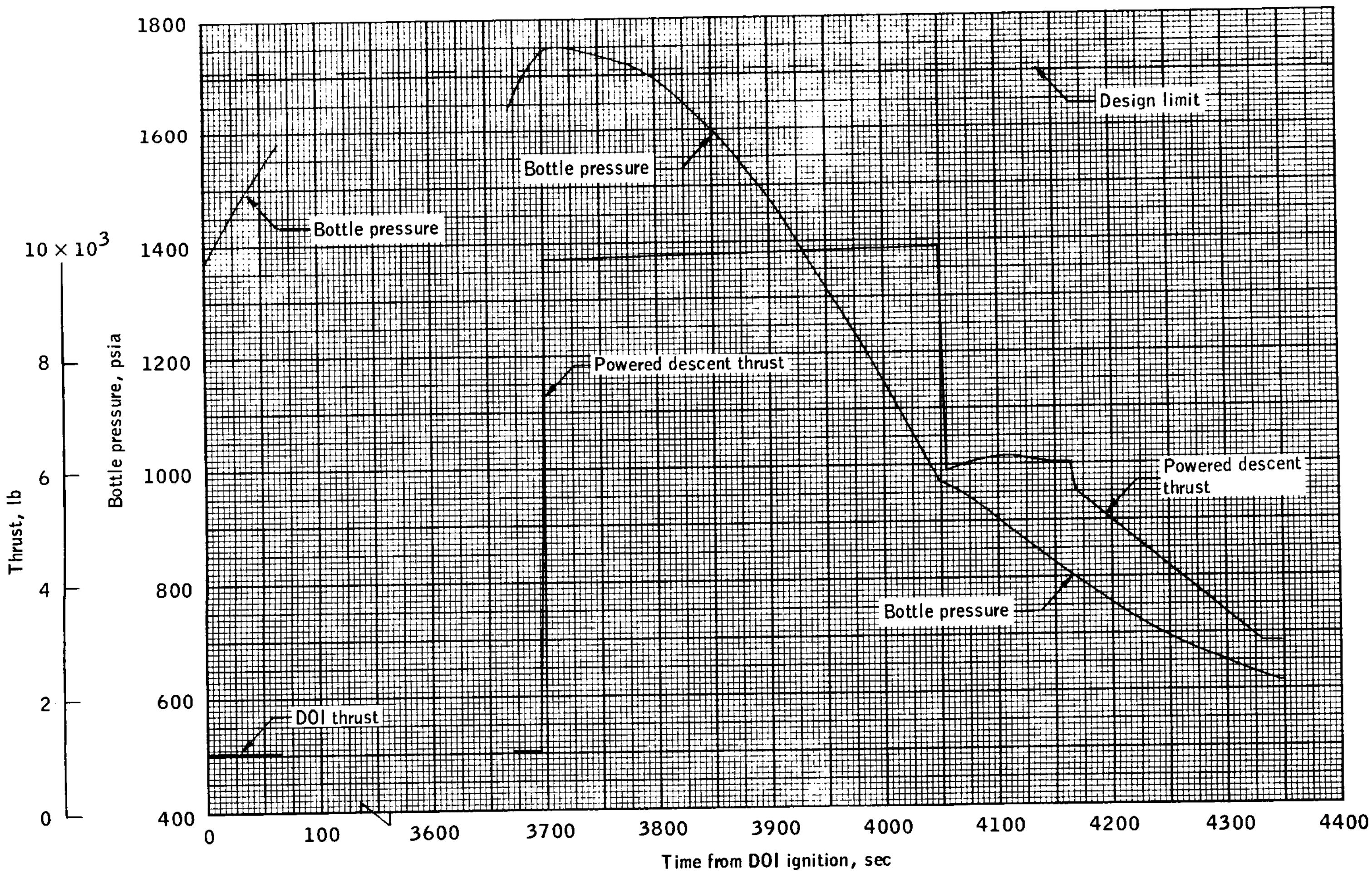
(a) Time from opening of earth launch window to DOI = 104hr.; pressure rise rate during coast = 8.5 psia/hr.

Figure 2.- SHe pressure profile for DOI with no throttle-up.



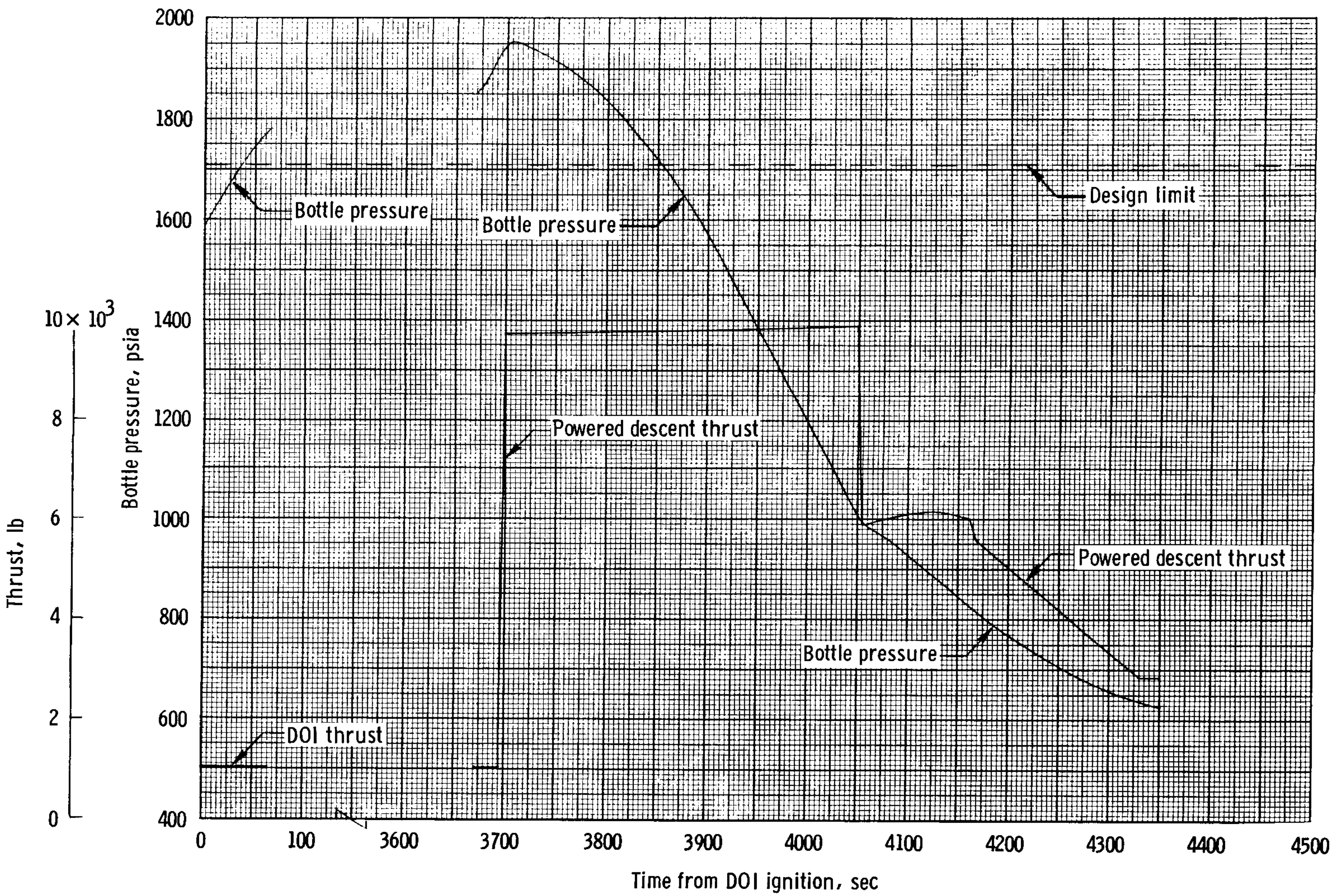
(b) Time from opening of earth launch window to DOI = 104 hr.; pressure rise rate during coast = 10 psia/hr.

Figure 2.- Continued.



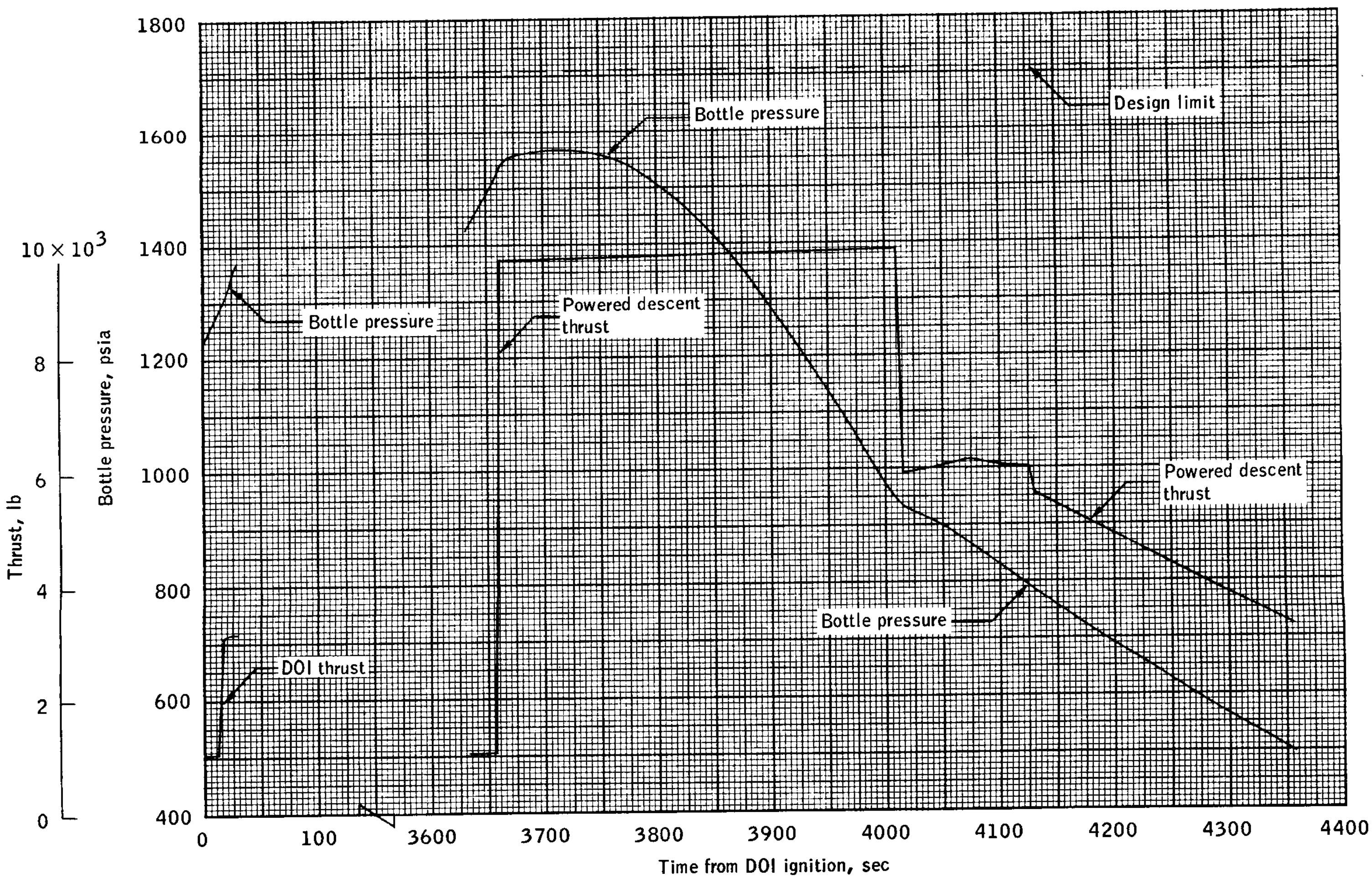
(c) Time from opening of earth launch window to DOI = 120 hr.; pressure rise rate during coast = 8.5 psia/hr.

Figure 2.- Continued.



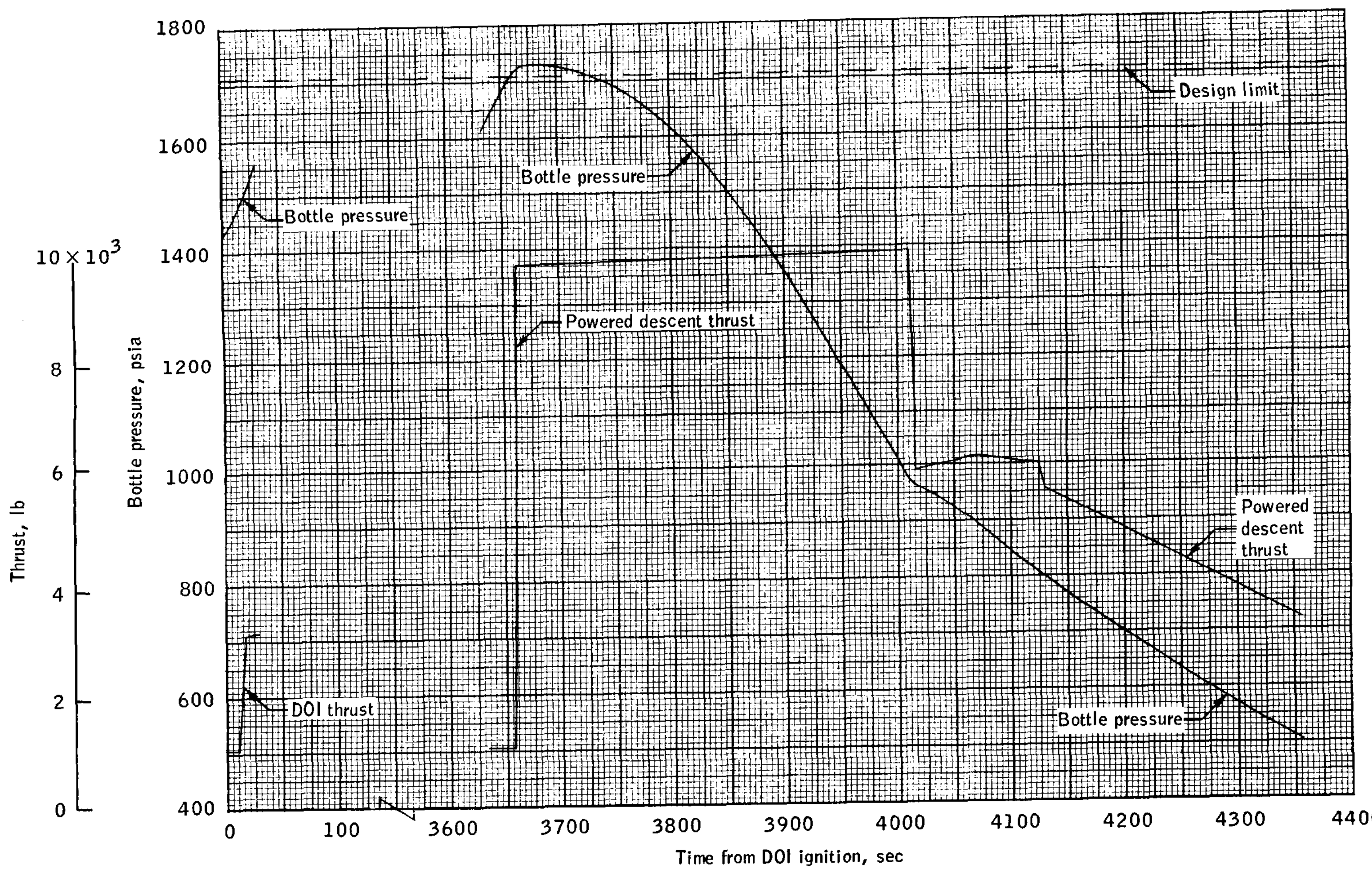
(d) Time from opening of earth launch window to DOI = 120 hr.; pressure rise rate during coast = 10 psia/hr.

Figure 2. - Concluded.



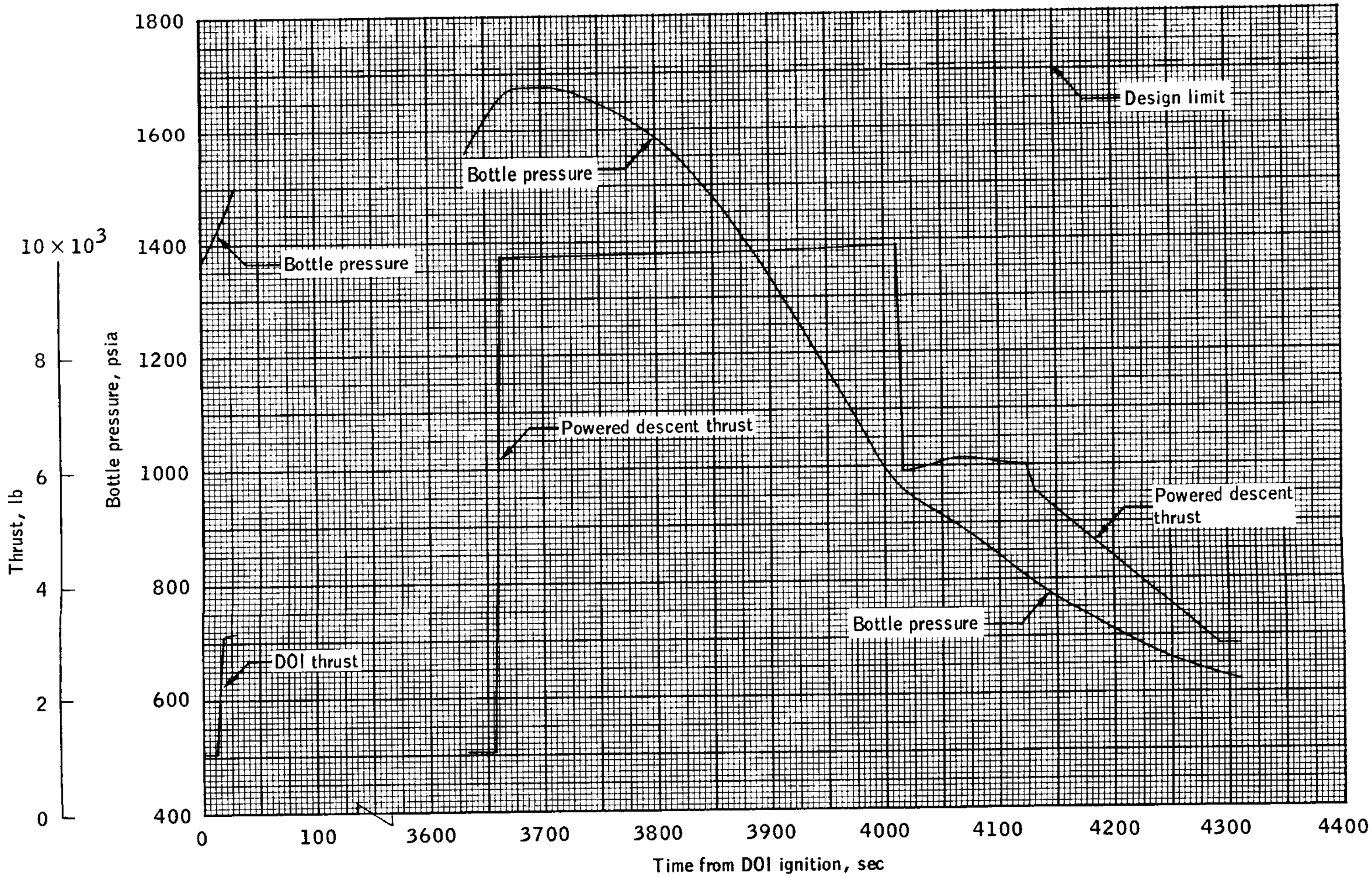
(a) Time from opening of earth launch window to DOI = 104 hr.; pressure rise rate during coast = 8.5 psia/hr.

Figure 3.- SHe pressure profile for DOI with a throttle-up to 30 % thrust.



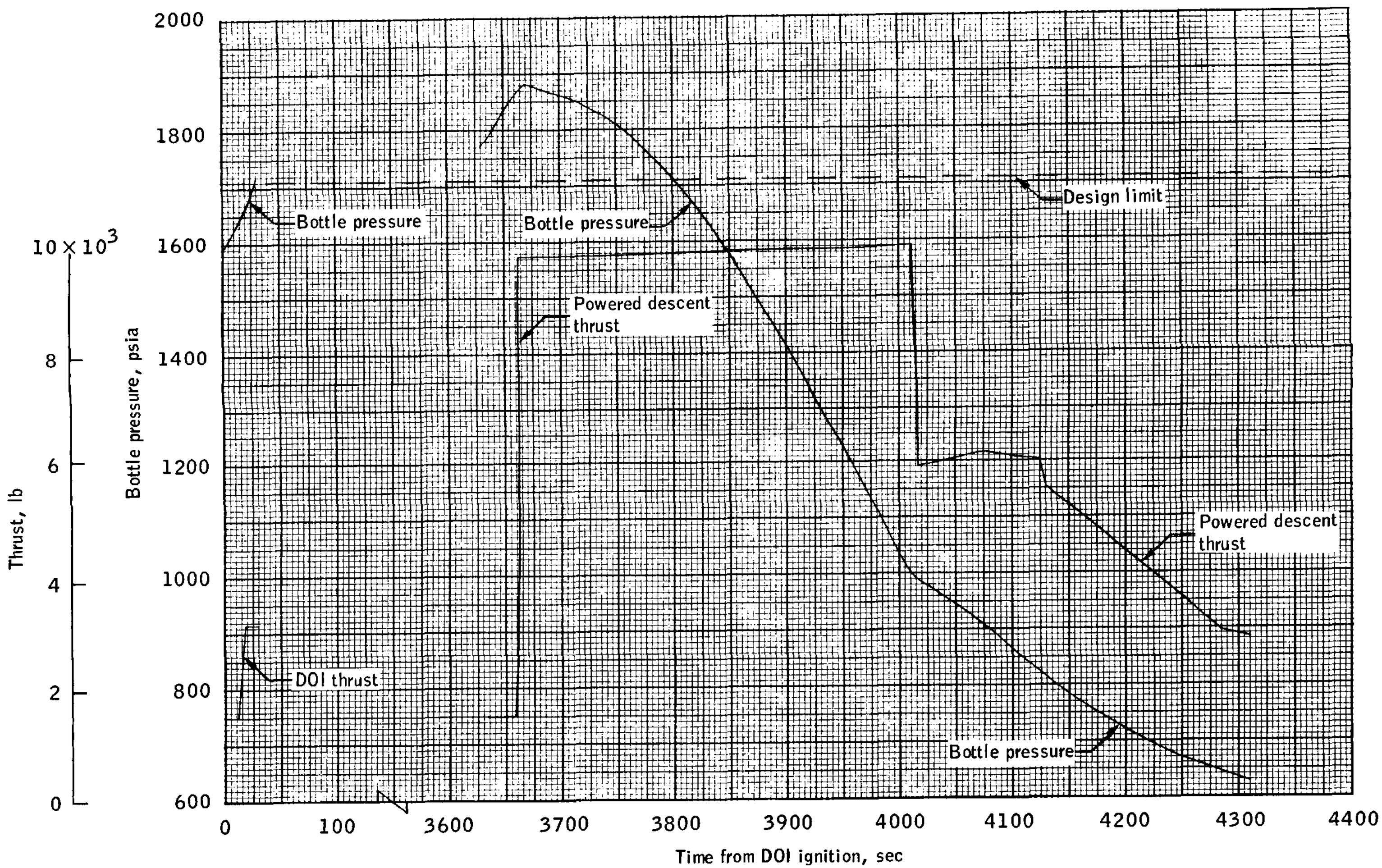
(b) Time from opening of earth launch window to DOI = 104 hr.; pressure rise rate during coast = 10 psia/hr.

Figure 3.- Continued.



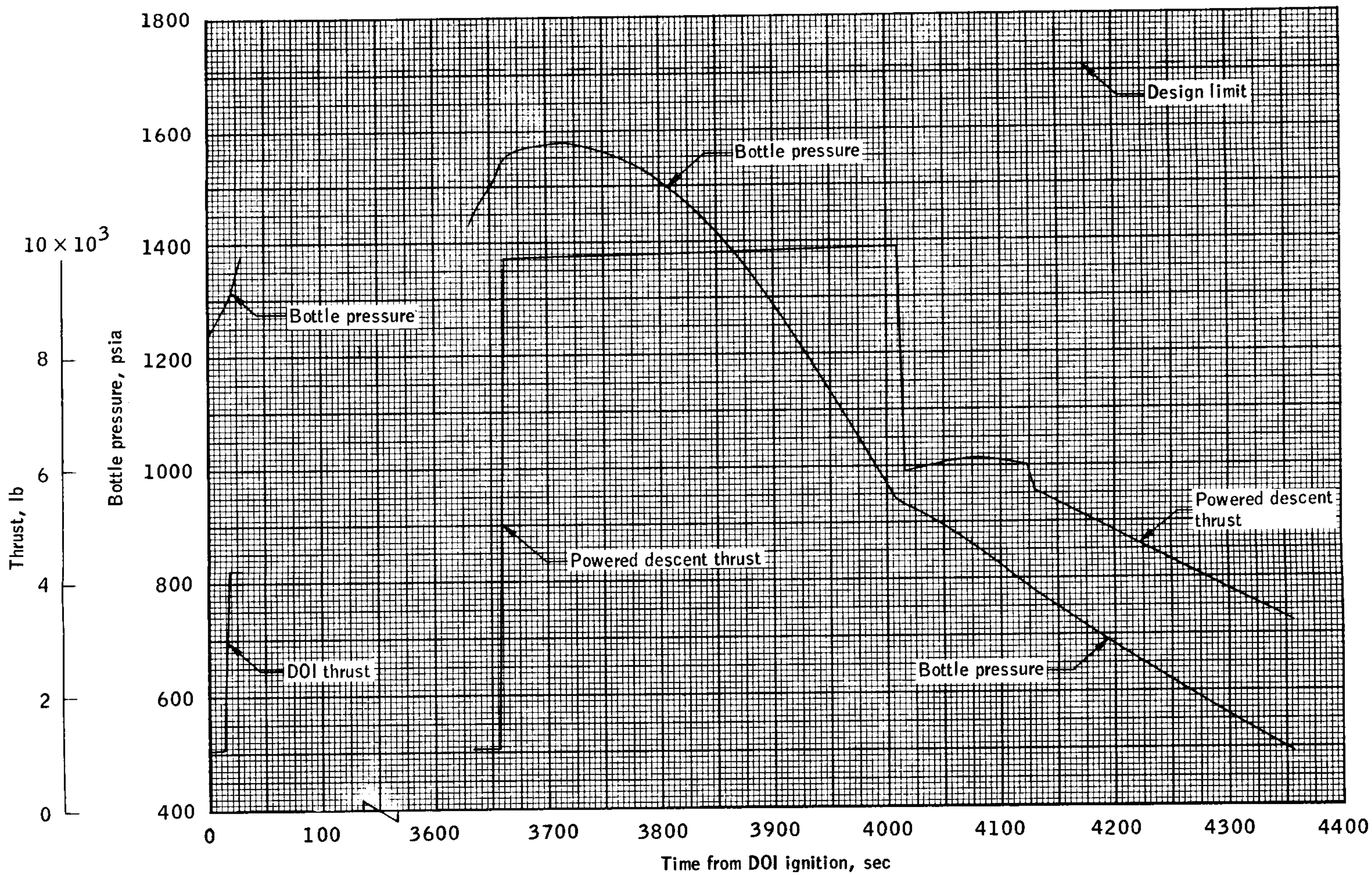
(c) Time from opening of earth launch window to DOI = 120 hr.; pressure rise rate during coast = 8.5 psia/hr.

Figure 3.- Continued.



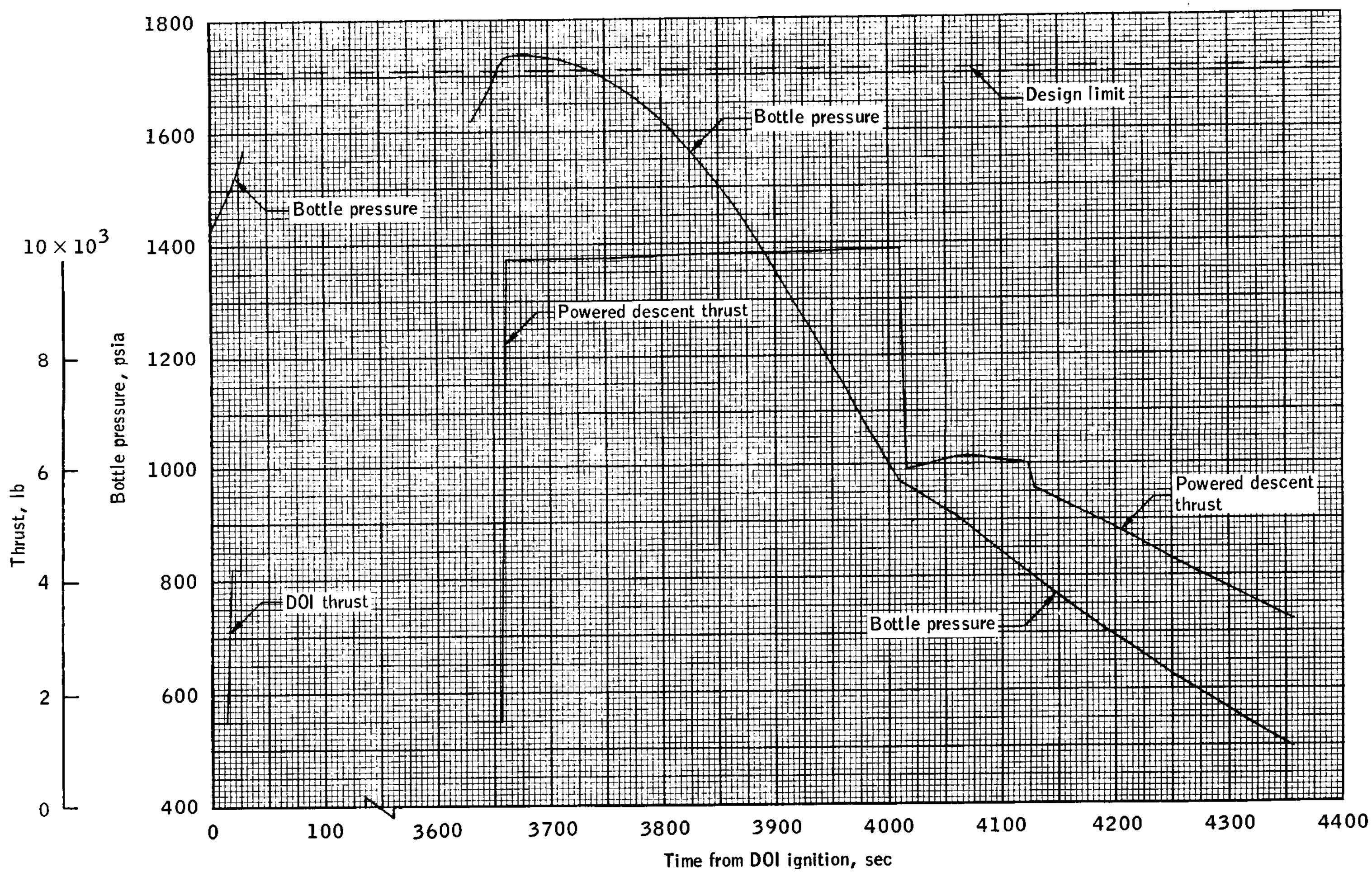
(d) Time from opening of earth launch window to DOI = 120 hr.; pressure rise rate during coast = 10 psia/hr.

Figure 3.- Concluded.



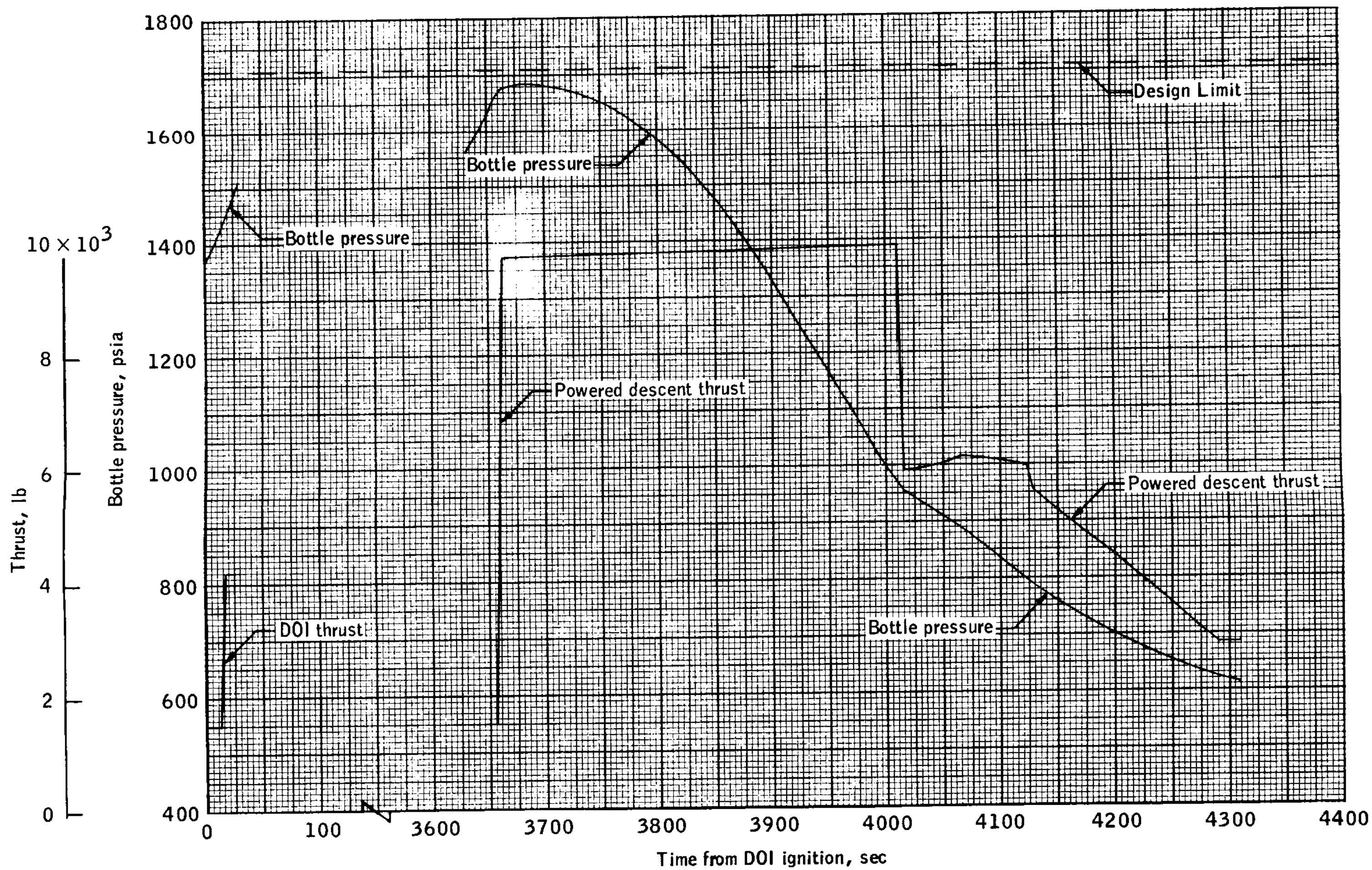
(a) Time from opening of earth launch window to DOI = 104 hr.; pressure rise rate during coast = 8.5 psia/hr.

Figure 4.- SHe pressure profile for DOI with a throttle-up to 40 % thrust.



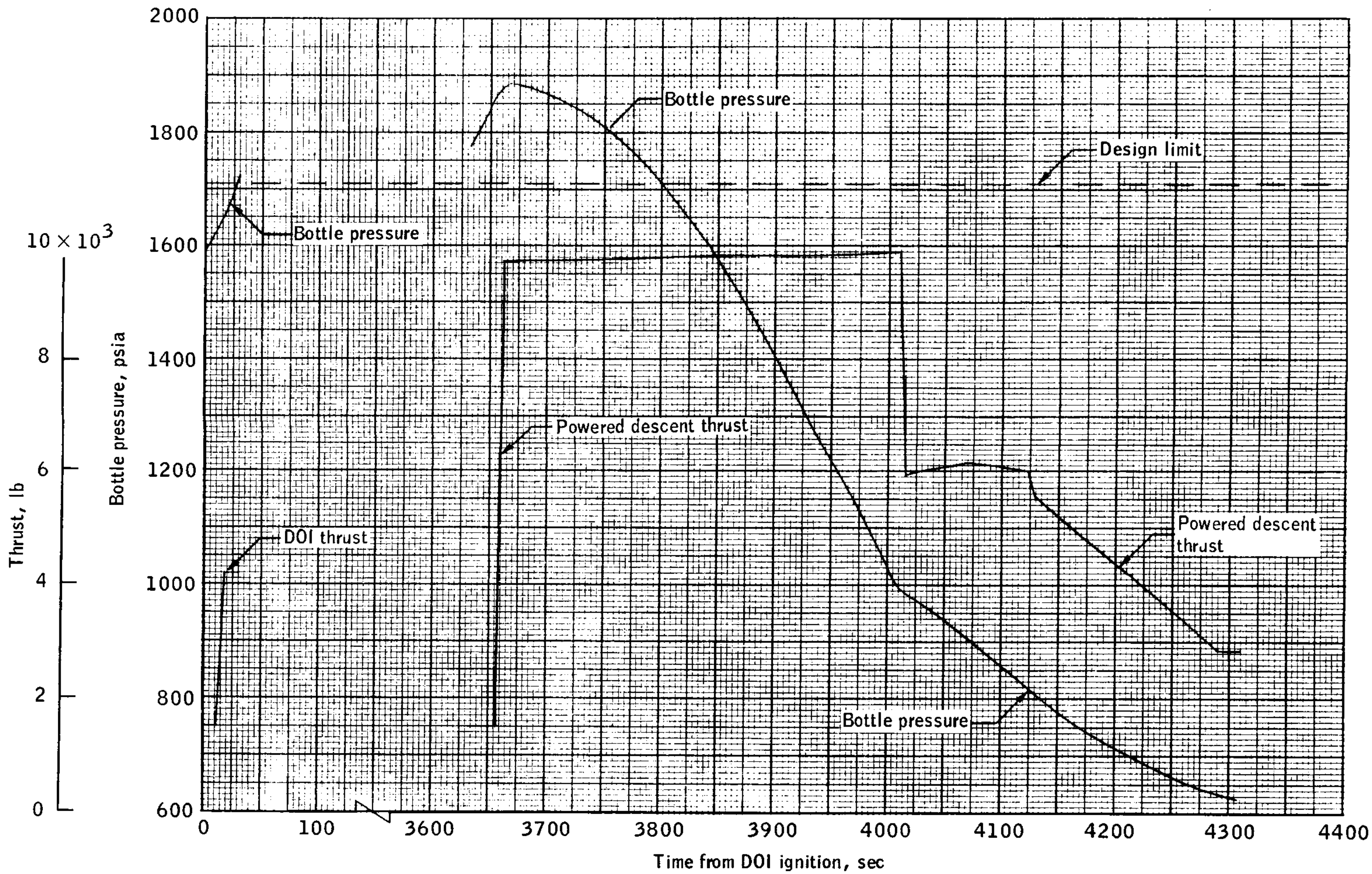
(b) Time from opening of earth launch window to DOI = 104 hr.; pressure rise rate during coast = 10 psia/hr.

Figure 4.- Continued.



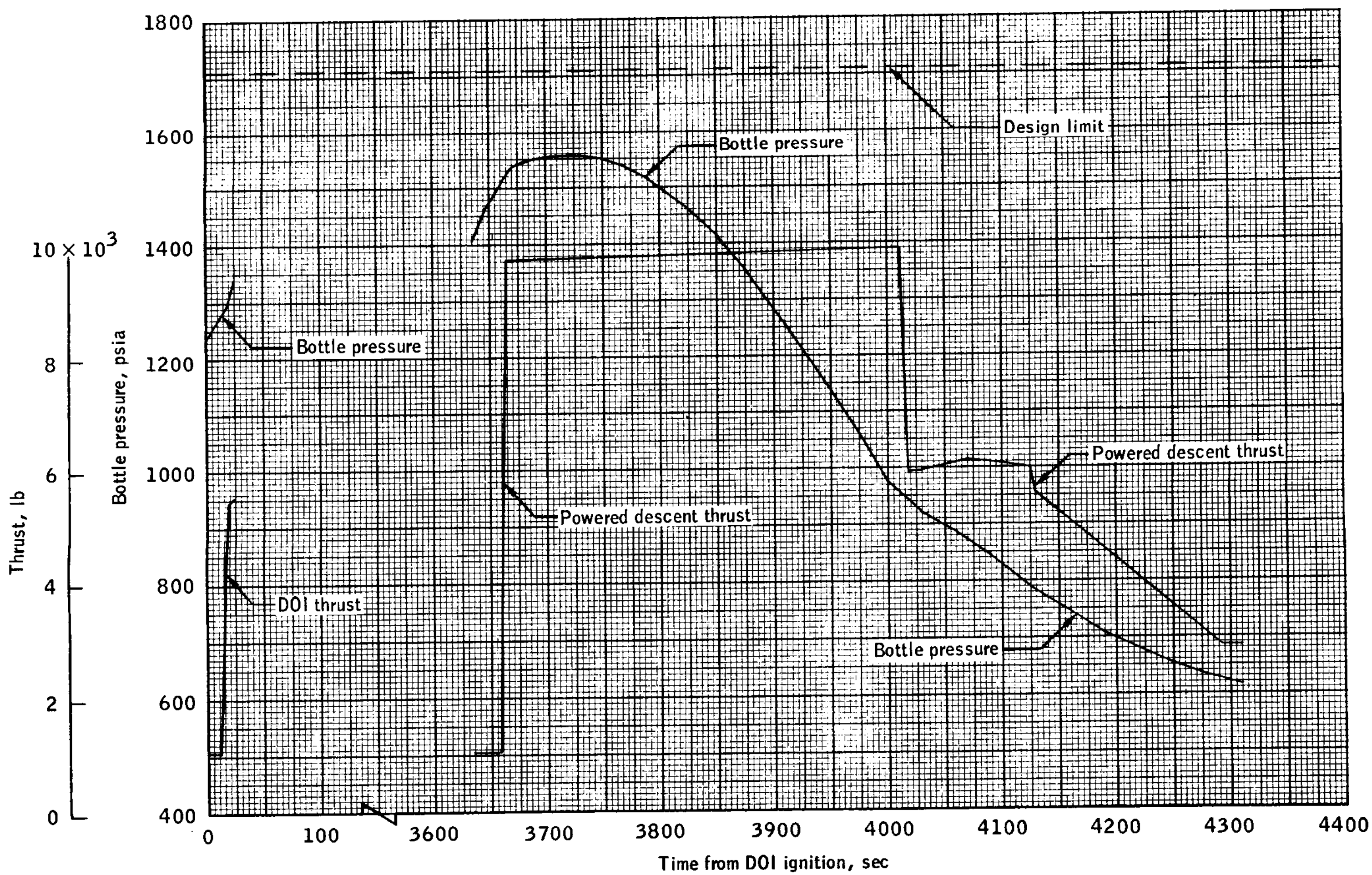
(c) Time from opening of earth launch window to DOI = 120 hr.; pressure rise rate during coast = 8.5 psia/hr.

Figure 4.- Continued.



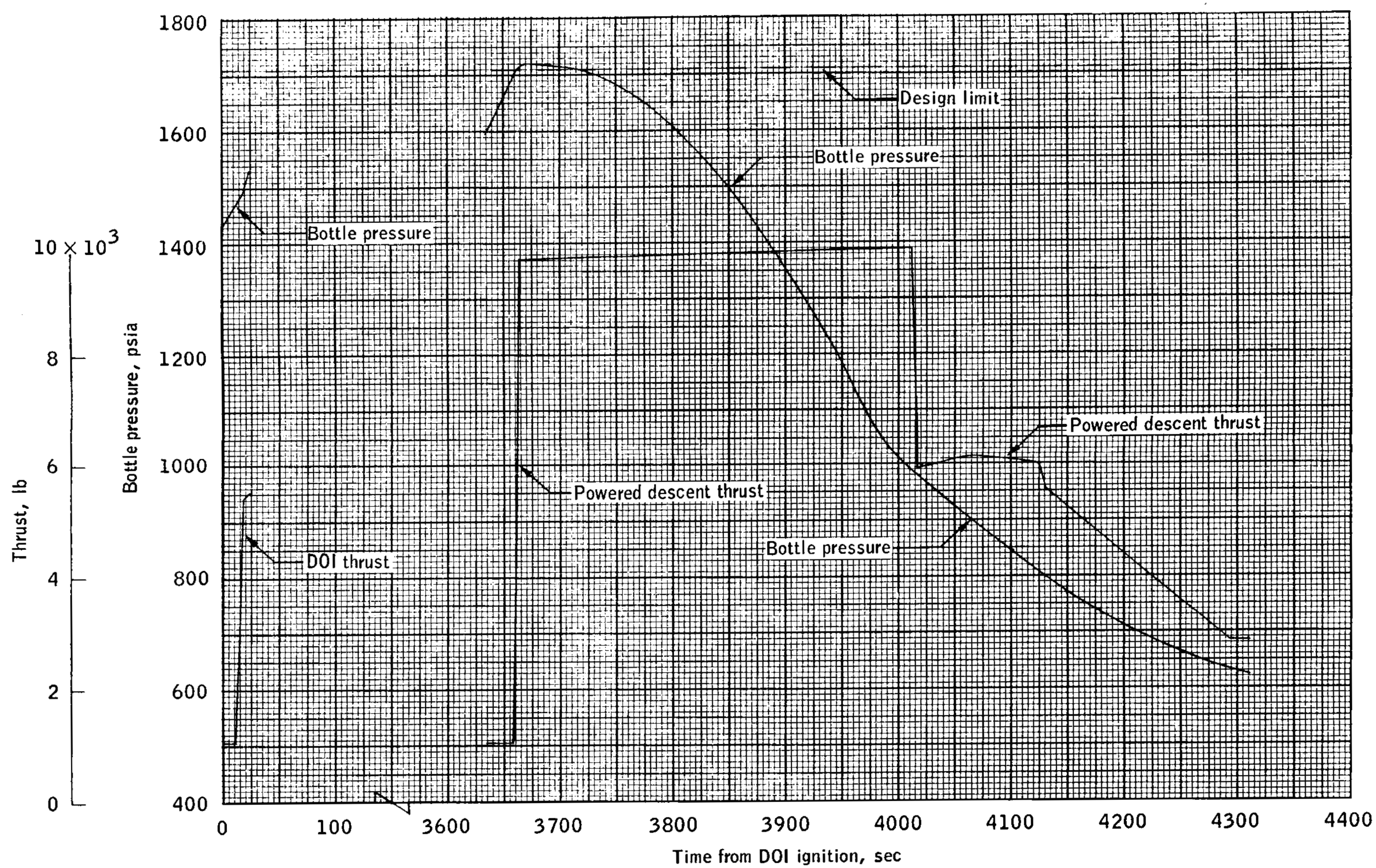
(d) Time from opening of earth launch window to DOI = 120 hr.; pressure rise rate during coast = 10 psia/hr.

Figure 4.- Concluded.



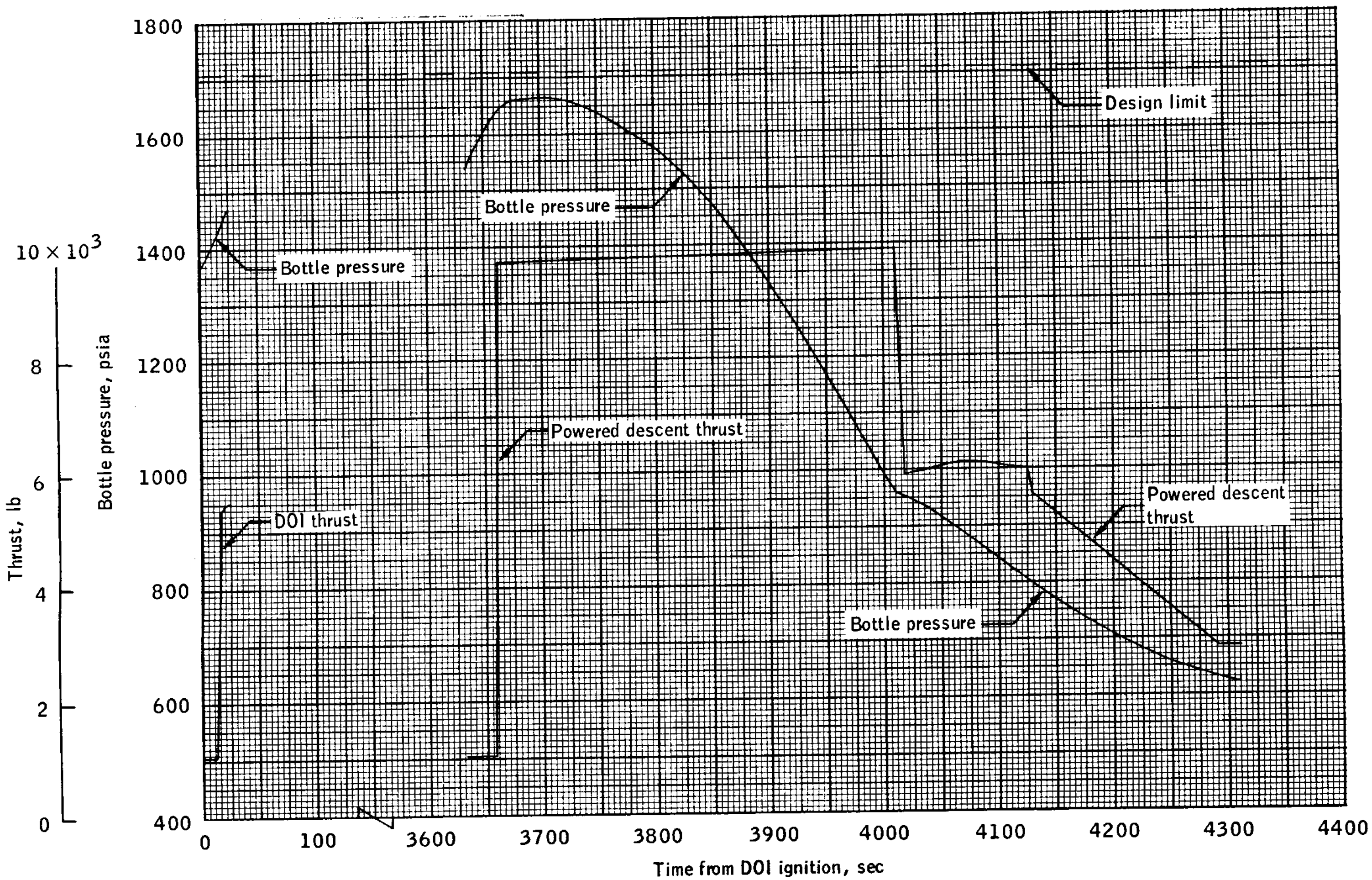
(a) Time from opening of earth launch window to DOI = 104 hr.; pressure rise rate during coast = 8.5 psia/hr.

Figure 5.- SHe pressure profile for DOI with a throttle-up to 52.7 % thrust.



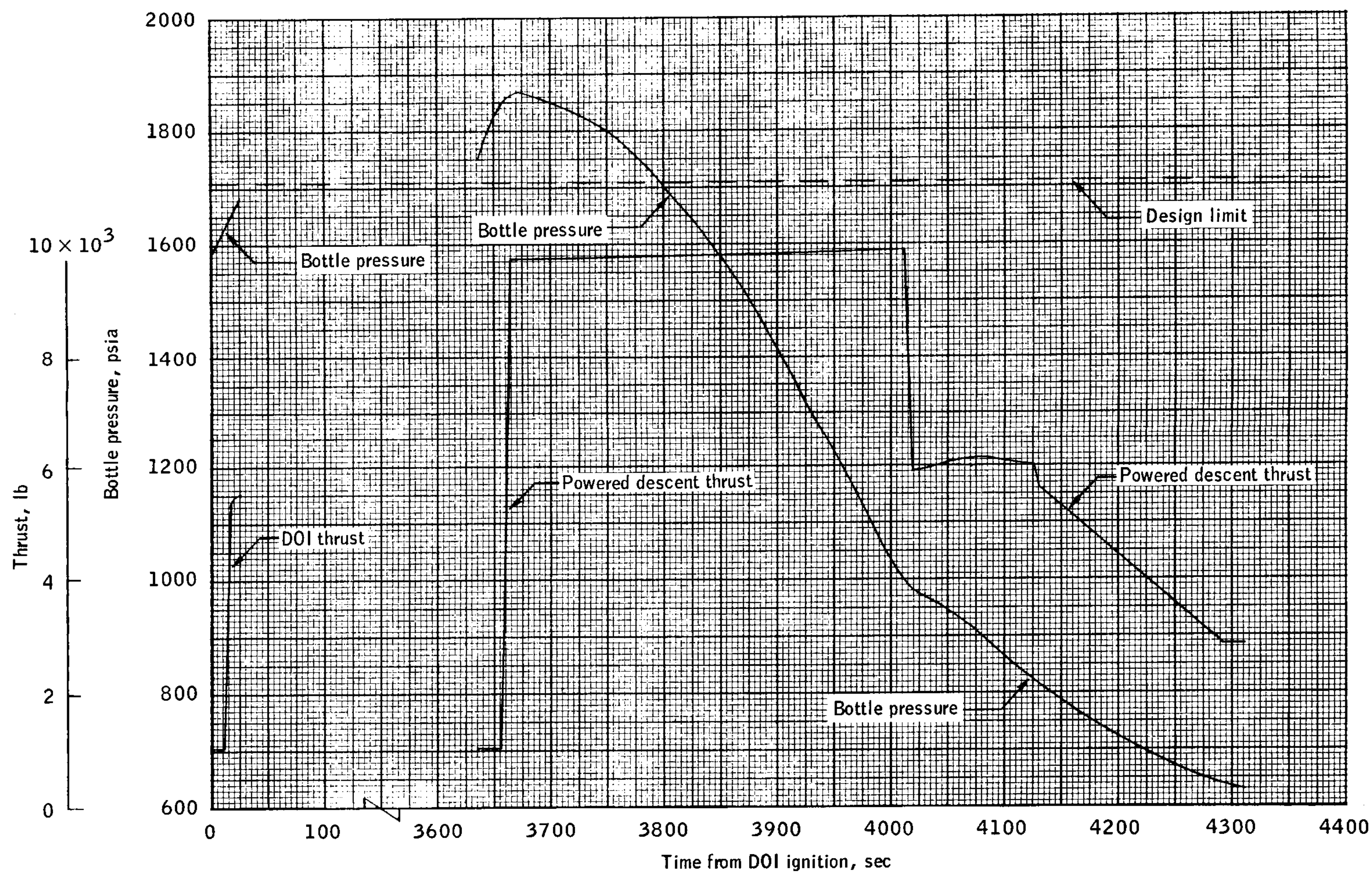
(b) Time from opening of earth launch window to DOI = 104 hr.; pressure rise rate during coast = 10 psia/hr.

Figure 5.- Continued.



(c) Time from opening of earth launch window to DOI = 120 hr.; pressure rise rate during coast = 8.5 psia/hr.

Figure 5.- Continued.



(d) Time from opening of earth launch window to DOI = 120 hr.; pressure rise rate during coast = 10 psia/hr.

Figure 5.- Concluded.

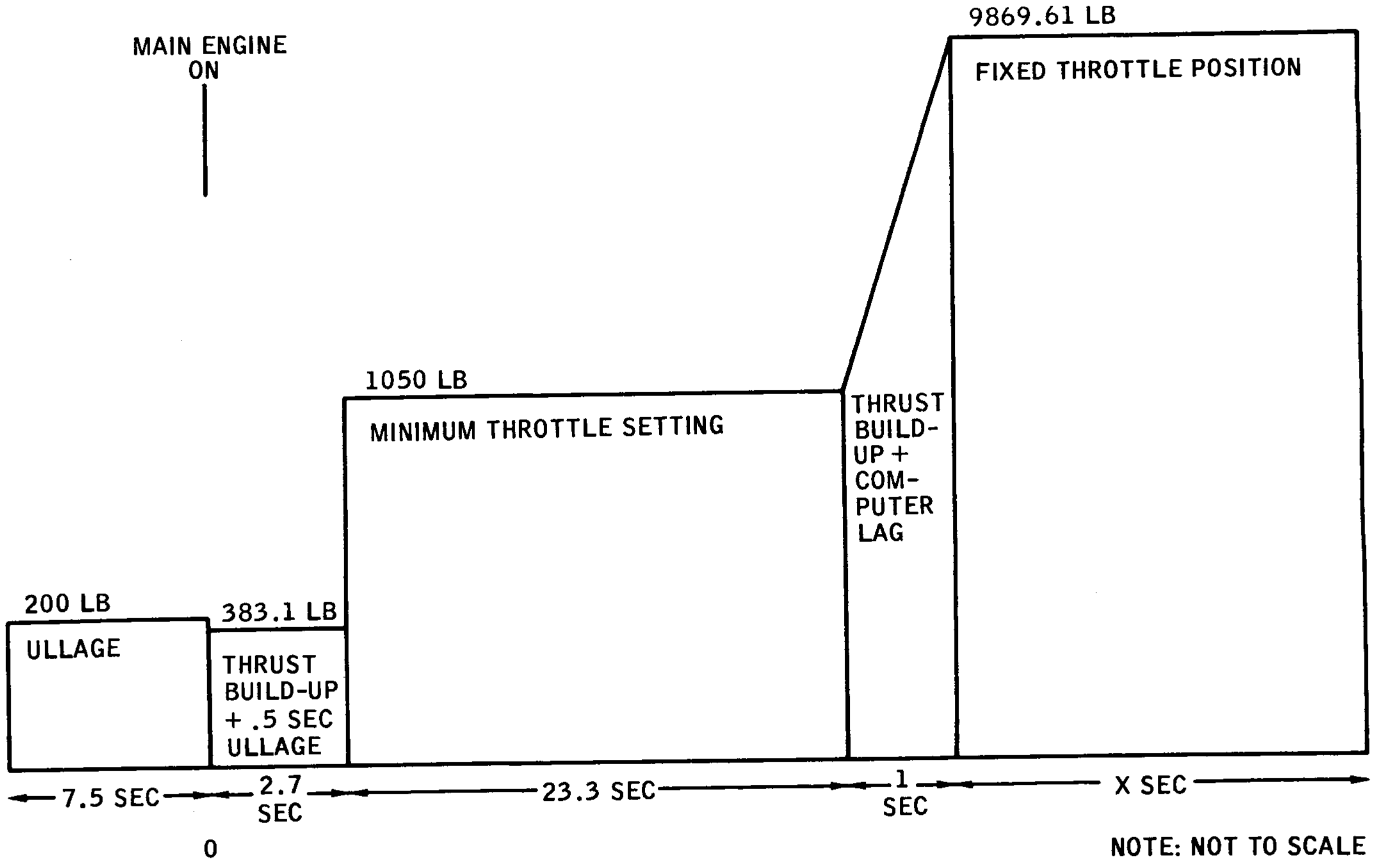


Figure 6.- DPS thrust profile with throttle-up to FTP.

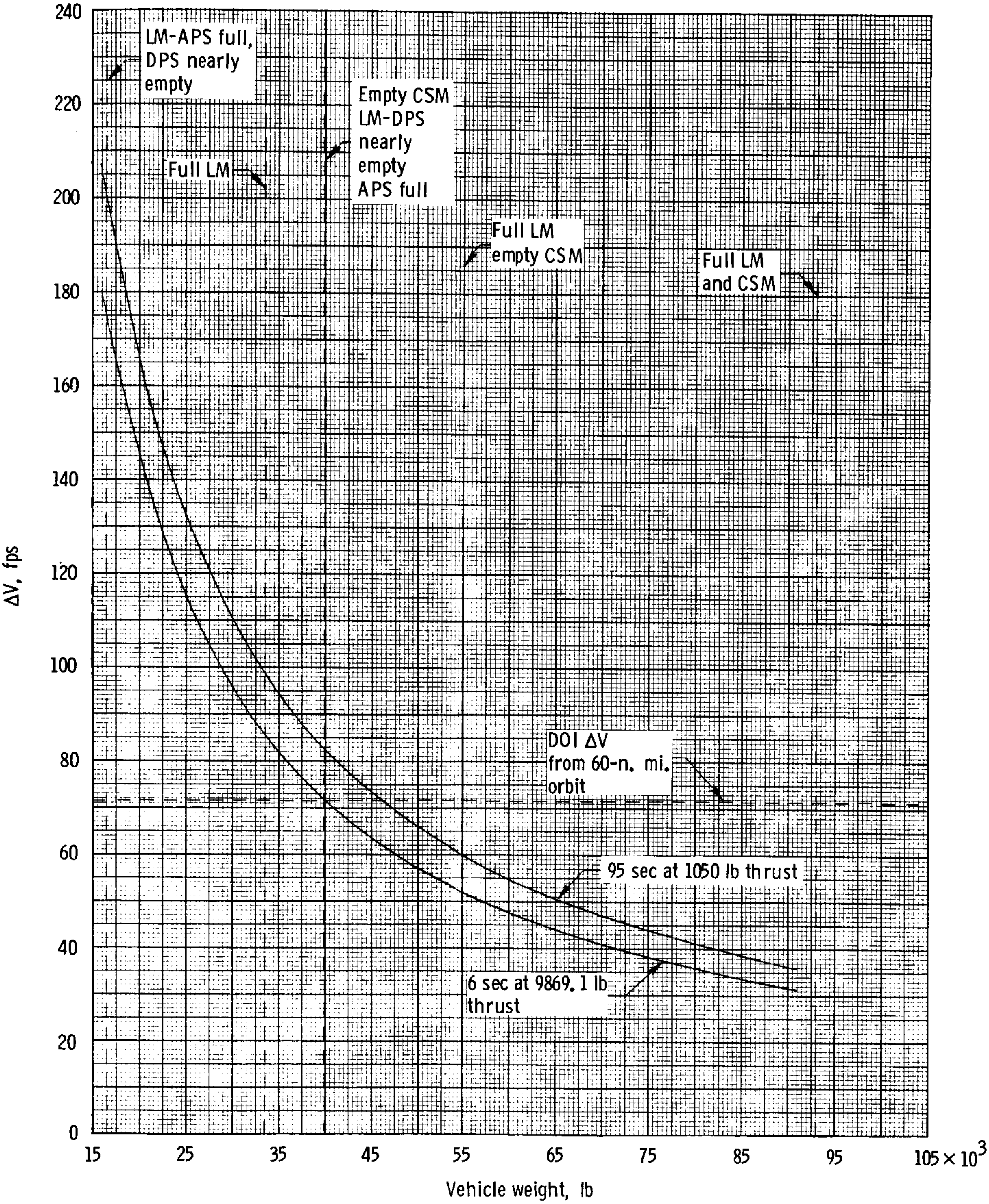
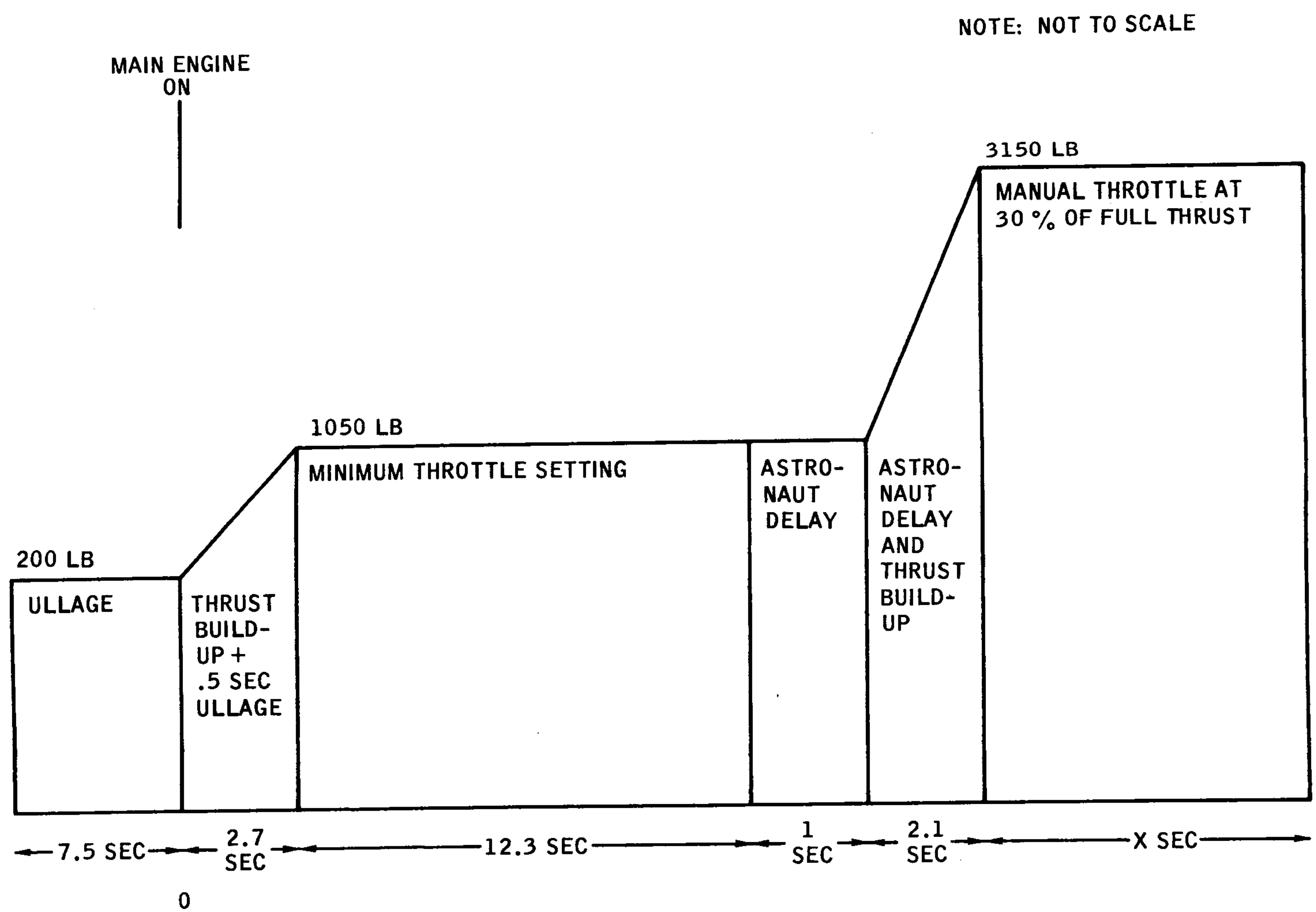
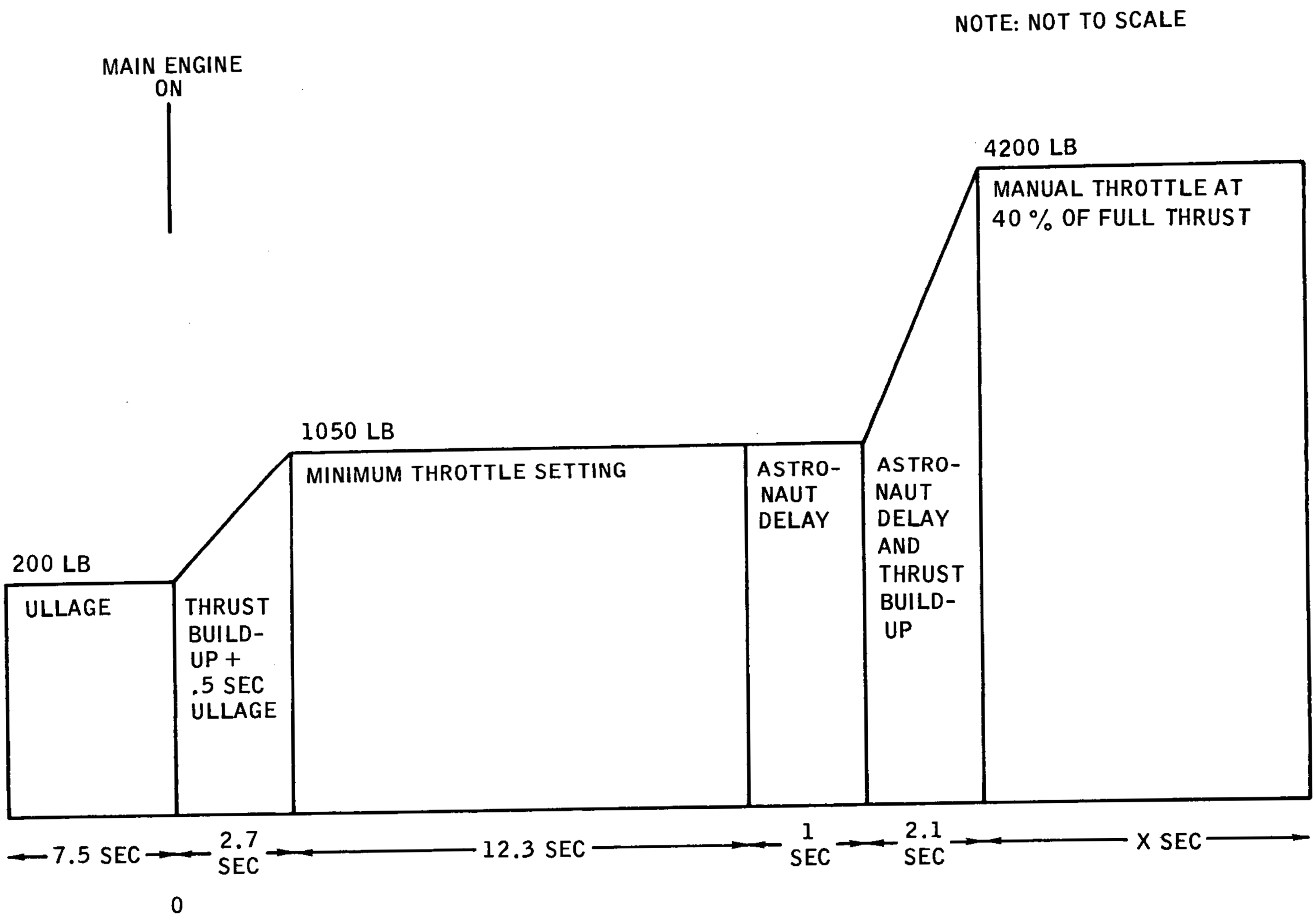


Figure 7. - DPS engine ΔV versus weight.



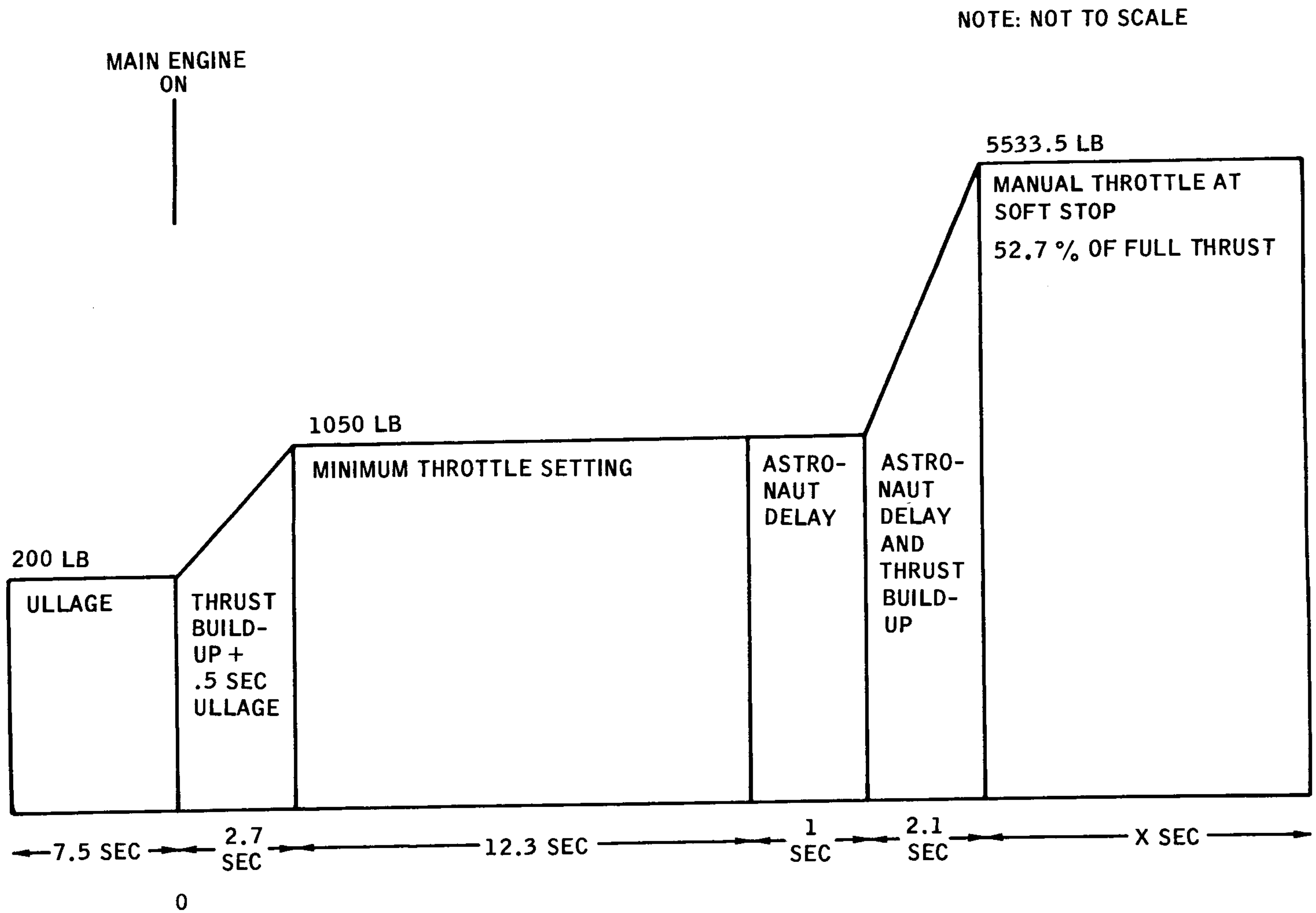
(a) Manual throttle-up to 30 %.

Figure 8.- DPS thrust profile for DOI.



(b) Manual throttle-up to 40 %.

Figure 8.- Continued.



(c) Manual throttle-up to soft stop (52.7 %).

Figure 8.- Concluded.

9.0 REFERENCES

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